Increasing the height and multiplying the number of spans of greenhouse: How far can we go?

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Abstract

This study is principally based on predicting the consequences on the microclimate of changing greenhouse design. Several variations on the greenhouse design have been described and examined i.e. the number of spans and gutter height.
Climate investigations were based on numerical simulations using the CFD model and included the dynamic effect of the crop on the flow as well as the subsequent heat and mass exchanges.
The results show (i) that the structural design elements, such as the height of the greenhouse and the number of spans, have significant consequences on climate performance. (ii) that we cannot indefinitely increase the height and the number of spans of the greenhouse. (iii) that increasing the volume of the greenhouse raises heat requirement and thus the economic profitability of this kind of investment is debatable.

Key words: CFD modeling, span, height, greenhouse

INTRODUCTION

During past years, special emphasis has been placed on improving the microclimate in greenhouses under summer conditions by means of simple design modifications.
Several studies dealing with this issue have been published. Among them, Mistriotis et al. (1997) studied the influence of the greenhouse length on the ventilation of a typical Mediterranean-type greenhouse. Lee & Short (2000) investigated the effect of various structural elements, for instance the vents on the microclimate inside the greenhouse.
Kacira et al. (2004) studied the effect of span numbers on gothic type multi-span greenhouse natural ventilation using a Computational Fluid Dynamics (CFD) simulation model.
Berroug et al., (2011) studied the impact of the layout of the greenhouses on their thermal performance numerically. They used an energy balance model to quantify its effect on the inside temperature of three types of greenhouses: a monospan, an Asymmetric monospan and a tunnel greenhouse.
Kruger and Pretorius (2012) studied the influence of various design parameters such as pitch angle and roof asymmetry on the velocity and temperature patterns inside a confined single span greenhouse heated from below.
Keshi et al. (2015) investigated the effects of vent configuration and span number on the microclimate in an 11-span plastic greenhouse cultivating 0.2 m-high lettuces under summer conditions in eastern China.
All the previous studies and the recent increase in greenhouse height and volume all over the world, particularly in hot regions, have led us to suppose that these parameters strongly influence the climate inside.
Progress in the field of the modeling convection and distributed climate within real-scale greenhouses by means of customized CFD software has driven us to use this new tool to predict

the consequences of changing greenhouse designs quicker rather than the use of traditional methods implying real scale prototypes. On the basis of these options, a study has been undertaken to make the best use of the CFD capabilities in order to evaluate greenhouse climate performance by simulating the consequences of the variations of the greenhouse structural elements i.e. the height and the numbers of spans in order to answer the following question: **Increasing the height and multiplying the number of spans in greenhouses: How far can we go?**

MATERIALS AND METHODS

Description of the numerical model

With regard to numerical simulations, some authors have used commercial or self-developed CFD codes to perform simulations for various greenhouse configurations. We can deduce from these studies, summarized in a review paper by Reichrath and Davies (2002), that the use of a 3D model and consideration of the crop effect are two essential points to define the consistency of the numerical results.

In this study, we have used a model that combines different scales of a 3D model i.e. the greenhouse and its immediate environment; the inner surroundings within the greenhouse, that takes into account a crop as a porous medium and determines the heat and water vapor exchanges at crop level (Boulard &Wang, 2002, Fatnassi et al; 2006). This model has been adapted to the CFD2000® software (Haxaire, 1999; Fatnassi et al., 2003) to evaluate the airflow, temperature and humidity patterns in a real greenhouse.

Distributed micro-climate investigations inside the greenhouse were based on numerical simulations to solve the mass, momentum and energy conservation equations.

The numerical Ansys Fluent © code was used to solve these highly non-linear equations using a spatial finite volume discretisation. Detailed information has been discussed more fully in the paper by Fatnassi et al. (2003 & 2006).

The greenhouses and their boundary conditions

The greenhouse

This study is principally based on the modeling of a greenhouse: 9.6 m wide, 20 m long and 5.93 m high-roof top (gutter height = 4 m high) and ventilation is guaranteed by means of 1.5 m high continuous vent openings located at roof top level. However, several variations with respect to this basic type will also be described and examined in this study i.e. gutter height and number of spans.

In this greenhouse there is a virtual 2m high rose crop; leaf area index measures 3 m^2 of leaves/ m^2 of soil. Both the dynamic effect of the crop cover on air flow and the latent and sensible heat exchanges with ambient air were modeled.

The boundary conditions

Climate characteristics of an average summer day in Mediterranean conditions have been selected.

The outside air temperature is assumed to be constant and equal to 33 °C and the external radiation was supposed to be direct i.e. clear and cloudless weather. The value of direct solar radiation was set to 860 W/m^2.

The different simulations

The consequences of several variations in the greenhouse and vents design or orientation have been investigated. We have focused on the effects of two principal modifications: i.e. the effects of the greenhouse height at gutter level (7m, 6m, 5m and 4m) and the effects of the number of spans on the greenhouse climate performance.

These architectural modifications were carried out automatically thanks to the parameterization tool under Design Modeller (DM) by defining new equations for the height and the width of the greenhouse:

Height = initial height + k* step1 [m] (1)

Width = initial width + k* step2 [m] (2)

The idea is then to vary k under Workbench to simulate the increase in height and number of spans of the greenhouse.

RESULTS AND DISCUSSION

Effect of the greenhouse height

To investigate more thoroughly the effect of the greenhouse height increase on the inside climate, we have simulated the inside climate of similar greenhouses in similar climatic conditions, only differing in height, i.e. respectively 4m, 5m, 6 m, 7m at gutter level. Fig 1 presents the corresponding inside air temperature patterns within these greenhouses.

Inside air temperature clearly decreased with the increase in greenhouse height. However, this temperature rise is not homogeneous; it mainly concerns the maxima, whereas the minima remain practically unchanged. On an average (Fig. 1) inside air temperature decreases by 2K when going from 4 to 5 m high, but only by 0.2K when rising from 6 to 7 m high. The effect on air temperature of increasing greenhouse height is clearly asymptotic and, from a climatic point of view, it is not necessary to try to increase the greenhouse height too much.

This temperature gain is very low compared to the financial investment involved in increasing the height of the greenhouse. This investment is approximately 0.86 €/m² if the height of the greenhouse is increased by 1m.

Furthermore, increasing the volume of the greenhouse also increases heating requirements to keep plants under optimal conditions. This is especially the case in Mediterranean areas that are subject to drops in temperature during the winter season.

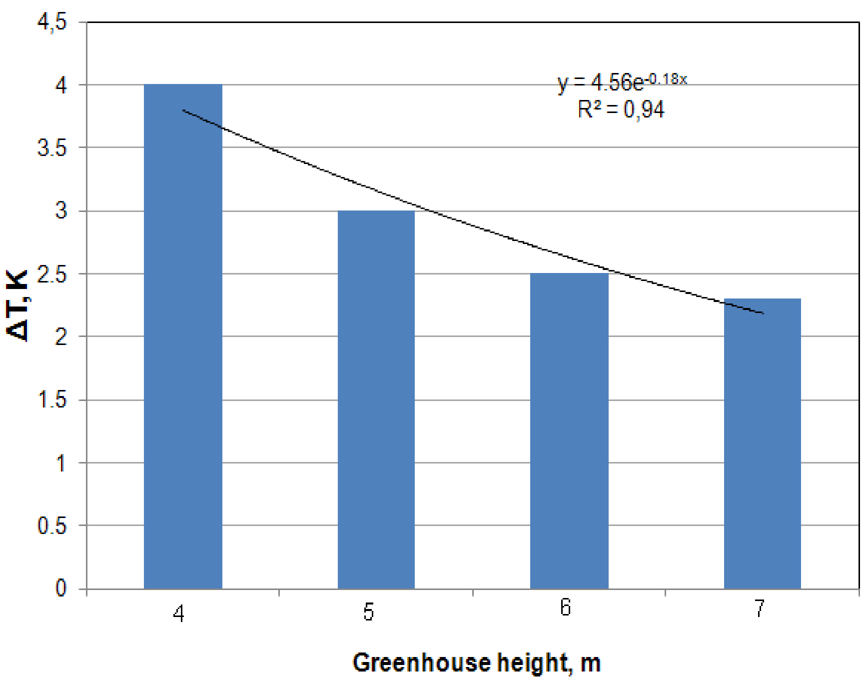

Figure 1. Temperature difference between inside and outside as a function of the greenhouse height

Heating requirements when increasing the greenhouse height:

Greenhouse heating requirements depend upon the amount of heat loss throughout the structure. A simplified energy equation can be used to estimate greenhouse heating requirements at night when they are higher (Bordes, 1992):

$$Q_h = K(T_i - T_e) \times S_c + 0.35 \times R \times V \times (T_i - T_e) \quad (3)$$

Where: K is the global heat transfer coefficient (W m^{-2} C^{-1}); S_c is greenhouse cover area (m^2); T_i is internal air temperature (°C); T_e is external air temperature (°C); V is greenhouse volume (m^3); R is air exchange rate (h^{-1}).

Figure 2 shows the relationship between the greenhouse height and the heat requirements. A significant increase in the heating demand was observed when the height of the greenhouse was increased. One of the reasons for this could be due to the fact that warm humid air tends to rise towards the top of the greenhouse and the cold air remains on the lower part at plant level. This phenomenon is accentuated when increasing the height of the greenhouse.

The way to deal with this issue is to equip this kind of greenhouse with thermal screens to keep the heat at plant level thus allowing maintaining temperature conditions favorable to plant growth and development.

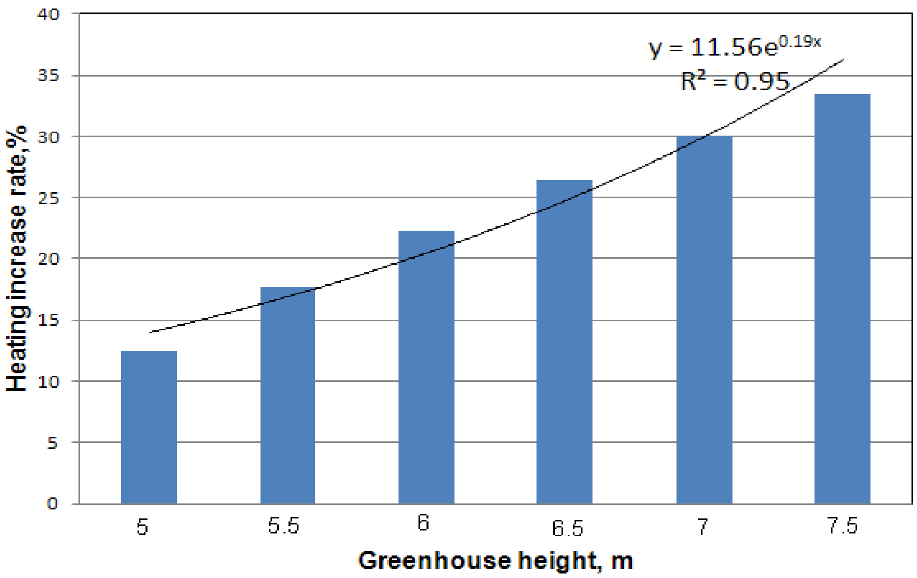

Figure 2. The rate of increase of heating requirement when increasing the greenhouse height.

Effect of the number of spans

For the same boundary conditions mentioned above, we have tested the effect of multiplying the number of spans on the air flow and climate patterns inside the greenhouse.

The effect of span numbers on the greenhouse air temperature

The effect of span numbers on the microclimate was evaluated according to the four different span numbers; a monospan, a 2-span, a 3-span, and a 10-span (Figure 3.a to e).

When comparing the air temperature in these four different greenhouse structures (Figure 4), a relative homogeneity of the air temperature over 70% in the area of the multispan greenhouse was observed in comparison to the monospan greenhouse. This homogeneity is more clearly visible inside the greenhouse with more than 10 spans.

Consequently, air temperature rises respectively by more than 2 K for the monospan, by 1.5 K for the 2-span, and by 1 K for 3-span greenhouse more than in the 10-span greenhouse.

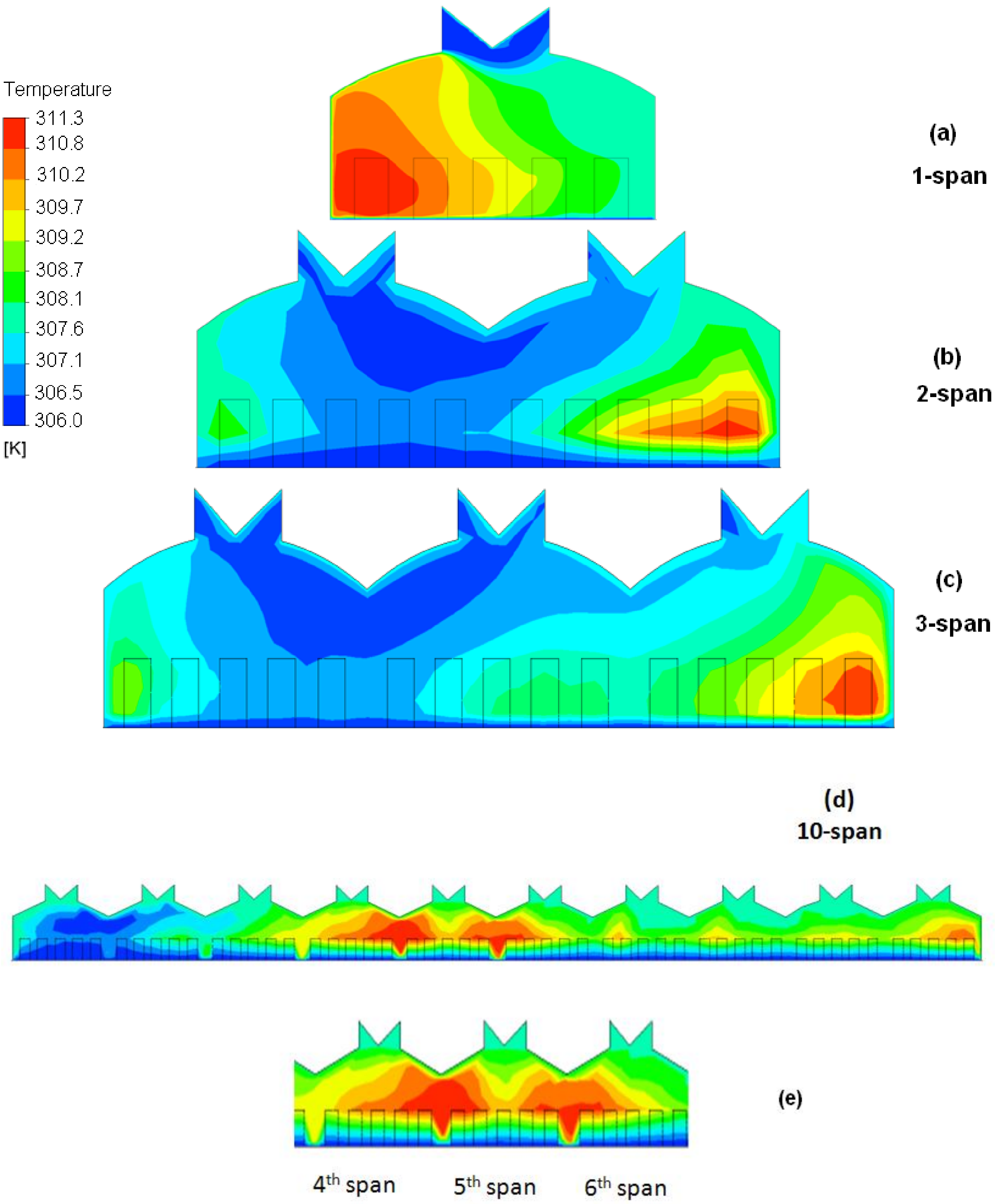

Figure 3. Air temperature field in K within the greenhouse for (a) 1-span, (b) 2-span, (c) 3-span and (d) 10-span. (e) air temperature field inside the 4th, 5th and 6th spans of the 10-span greenhouse

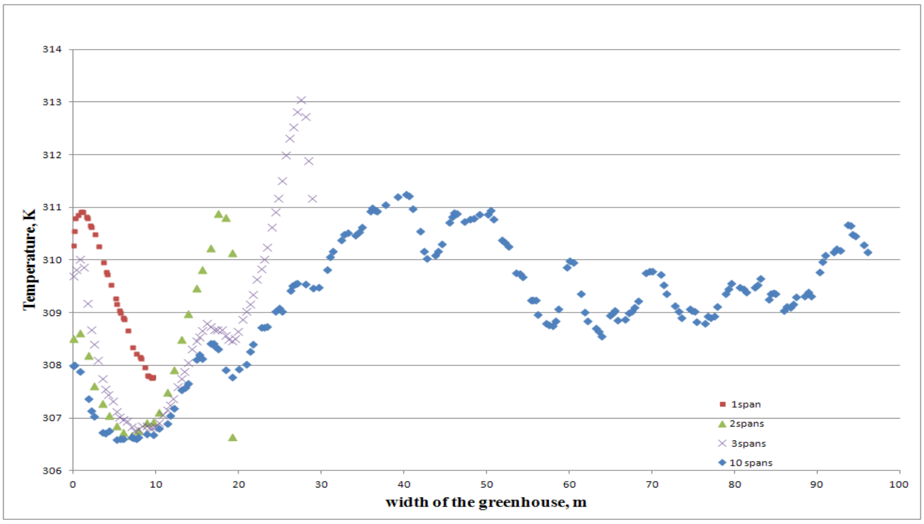

Figure 4. Horizontal profile of air temperature at two meters high inside the greenhouses: ■ 1-span, ▲ 2-span × 3-span and ♦ 10-span.

The effect of span numbers on the greenhouse airflow pattern

In the case of a monospan greenhouse (Figure 5.a), air entered from the windward side vent and flowed partially through leeward side of the greenhouse before the outflow occurred from the right side vent.

For those with 2 and 3-spans, air entered predominantly from the first windward opening in the greenhouse, traveled along the interior towards the right side and most of the outflow occurred from the last roof vent located on the leeward side (Figure 5.b). In the two greenhouses studied, the occurrence of an air vortex was observed in the last span on leeward side. This can explain higher air temperatures observed on this level compared to the other zones in the greenhouse.

In the 10-span greenhouse, air entered through the windward opening in the first span and in the 6th span, traveled along the first 3 spans and last 5 spans towards the right side of the greenhouse before exiting from the leeward opening in the 2nd, 3rd, 4th, 7th, 8th, 9th and 10th span (Figure 5.c). In this case, the occurrence of an air vortex was also observed in the 4th, 5th and 6th spans inside the greenhouse. In such cases, there is lower air renewal in the canopy zone of these spans. Moreover, higher greenhouse air temperatures, in these particular zones compared to the others in the greenhouse, were observed (Figure 3.e).

In general, the air flow is homogeneous in the first three and the last four spans of the greenhouse. To overcome overheating observed in the three spans in the middle of the greenhouse, we will have to change the orientation of the openings on the leeward and windward sides.

These results are in line with the ones found by Kacira et al. (2004) who studied the effect of span numbers on greenhouse air flow. They also highlighted the creation of the air vortex in the middle of 6-span, 12-span and 24-span greenhouses.

To ensure climatic homogeneity inside the multispan greenhouse, it should be composed of at least 10 spans. To prevent hot spots due to air trapping by air vortex, we would only have to change the orientation of the leeward and windward openings of spans in the middle of the greenhouse.

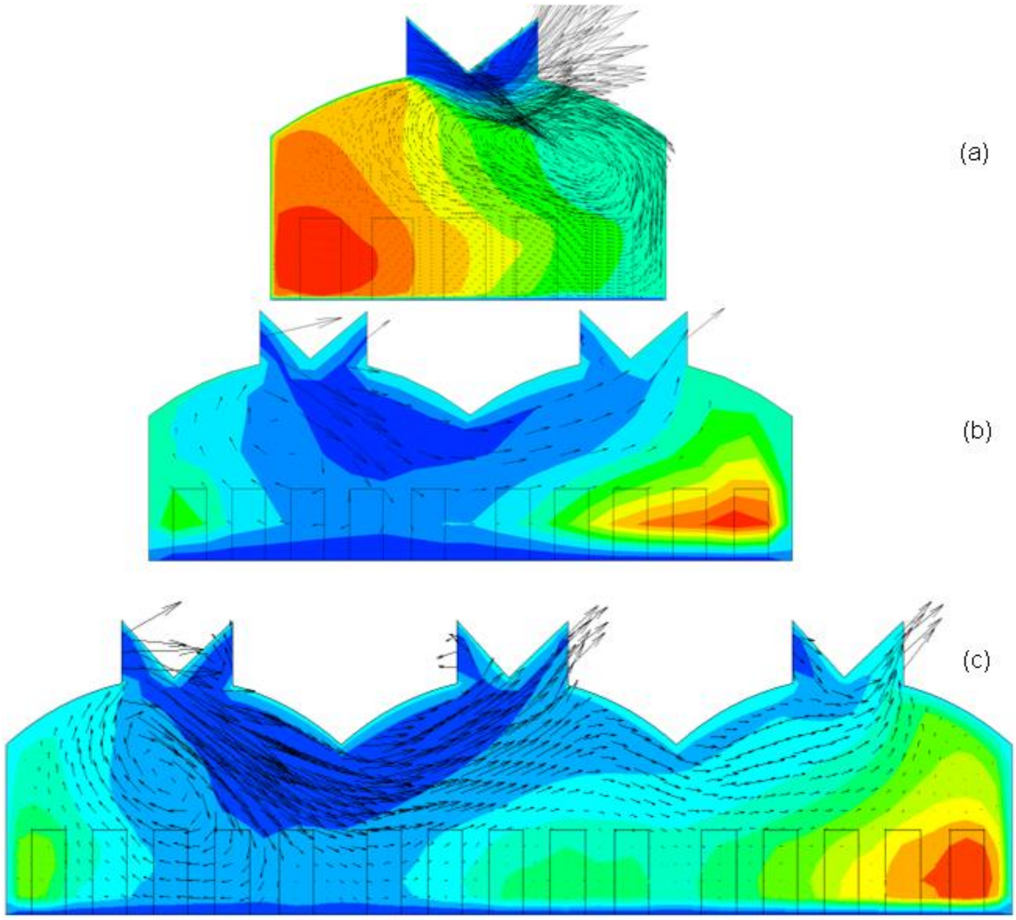

Figure 5. The airflow pattern in a greenhouse, (a) 1-span; (b) 2-span; (c) 3-span; (d) 10-span

CONCLUSION

The air temperature and the air speed patterns in different greenhouse structures were evaluated and the results showed that the structural design elements, such as the height of the greenhouse and the number of spans have significant consequences on climate performances.
It was demonstrated that increasing greenhouse height by more than 6 meters was unnecessary.
To create a homogeneous climate inside the greenhouse, more than 10 spans are required.
This study also showed that CFD facilities can be used to improve greenhouse designs and equipment quicker than with the traditional methods involving real scale prototypes.

Further studies will be focusing on the use of the same approach in order to thoroughly look into the influence of changing greenhouse designs as well as the combination of climate control methods (cooling systems, shadowing) and ventilation.

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